BLAST-INDUCED FRAGMENTS FROM DETONATIONS INSIDE MUNITIONS STORAGE STRUCTURES

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BLAST-INDUCED FRAGMENTS FROM DETONATIONS INSIDE MUNITIONS STORAGE STRUCTURES

By:

Khosrow Bakhtar and Michael M. Swisdak

ABSTRACT

The products of an accidental detonation in an aboveground storage magazine, with or without earth cover or in open stacks include: fire, airblast, and projections. For such mishaps, significant hazards are induced by fragments possessing high speeds and low angle paths. The hazardous effects associated with such projections are significantly reduced by storing explosives in chambers or magazines constructed below ground surface. The review of available reports and standards lead to identification of five principal effects namely: (1) air blast pressure; (2) fragments (primary and secondary); (3) chemical hazards; (4) thermal hazards; (5) ground shocks. Extensive studies have been performed in the past on hazardous effects of blast pressure, induced thermal and chemical environments, and ground shocks. However, the degree and extent of fragment-induced hazards associated with accidental detonations of explosives stored in rock/soil structures (above ground and below ground magazines) are still not fully verified. The empirical relationships used are too general and do not account for site specific characteristics of geologic and engineered systems. A recent Air Force program dealing with scale model studies of explosives storage structures using physical modeling under 1-g by scaling geometry and strength related material properties, has been of great help in understanding and predicting the hazardous effects of blast-induced fragments. The scale model tests have the advantage of being performed under controlled conditions, which makes it possible to observe the influence of various parameters on induced fragmentation and to perform 100 percent debris recovery within sectors of interest. In addition, assuming the static and dynamic similitude conditions between the model and its respective prototype are maintained, the response observed is real, not postulated. Therefore, its results can be used for prediction of prototype behavior at a fraction of the cost.

For underground storage magazines, the pattern of fragments produced and their trajectories are different than those from aboveground because of constraints imposed by the earth's lateral confinement. The theme of this paper is to consider a methodology for analysis of blast-induced fragments produced by detonations inside storage magazines. References are made to recent Air Force tests which include the 1994 MSM, test conducted at UTTR, and the scale model tests of underground storage chambers, conducted to simulate the prototype KLOTZ tunnel explosion test in China Lake, California..

1. INTRODUCTION

The Air Force Explosives and Safety Standards (1990) and the Department of Defense Ammunition and Safety Standards (1992) define fragments as primary and secondary depending on their origins. **Primary fragments** are formed as a result of shattering the explosive casing or container; they are usually small , and travel initially at velocities on the order of thousands of feet per second. **Secondary fragments** are formed as a result of high blast pressure on the structural components; they are larger in size than primary fragments, and travel initially at velocities on the order of hundreds of feet per second. The DOD standards further defines a hazardous fragment as one having an impact energy of 79 joules (58 ft-lb) or greater.

The damage or injury potential of explosion induced fragments is normally determined by the distance between the "potential explosion site" (PES) and the "exposed site" (ES), DOD 6055.9-STD, and the

i) ability of the PES to suppress the blast overpressure;
ii) ability of the ES to resist the explosion effects.

Figure 1 is drawn to show a conceptual visualization of a blast-induced fragment rajectory originating from a Potential Explosive Site (PES), such as a subsurface explosive storage facility, and landing within its respective grade Exposed Site (ES).

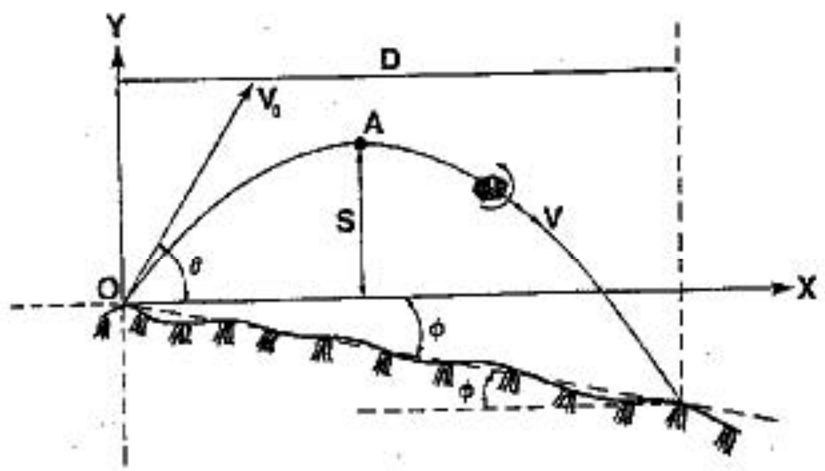

FIGURE 1. SIMPLIFIED DIAGRAM OF A FRAGMENTS TRAJECTORY.

The scenario depicted by Figure 1 is typical of the situation which may exist around a tunnel explosion site. Ballistic tables or other numerical computing methods such as the Ward et al. (1985) approach and the FRAGHAZ code developed by McCleskey (1988), can be used to determine the range of displacements of fragments. For a simulated explosion test (such as the KLOTZ Tunnel test in China Lake) high speed cameras, located at designated locations around the test bed, have been used for measuring ejecta trajectory angle θ and initial and final velocities V_0 and V. The accuracy of measurements of these parameters are questionable because of the amount of dust produced following the detonation making the ejecta trajectory identification and their separation from the dust extremely difficult.

For model testing at 1-g, the explosive charge is also scaled. Therefore, following detonation, less dust particles are produced. This makes identification of ejecta trajectories much easier. Scaling of ejecta velocities, mass, and throw distances are based on the geometric scale factor (l^*) and density scale factor (ρ^*).

2. FRAGMENTS

2.1 MUNITIONS STORAGE MODULE (MSM) TEST

A 20-foot earth covered Munitions Storage Module test was conducted at the Utah Test and Training Range (UTTR) in 1994 to study the blast effects on aboveground storage magazines (Jenus, et al., 1995). Pre-test site characterization was performed to determine the relevant characteristics of the geologic and engineered systems including the seismic impedance contrast between the module and the host soil. The test was conducted at high loading density. Post-test fragment recovery was made in thirty-six radial sectors located every 10° around ground zero (from 0° to 360° clockwise). Each radial was approximately 488 meters (1600 ft) long and 3 to 9 meters (10 to 30 ft) wide. Data collection included locating all debris in excess of 134 grams (4.8 ounces) up to the saturation zone. Photographic documentation was made of site preparation and construction, instrumentation setup, calibration, and explosion event. Fragment recovery was facilitated by using an automated mapping technique.

2.2 US AIR FORCE SCALED MODEL TUNNEL EXPLOSION TESTS

A series of five scaled model tunnel explosion tests was conducted outside Edwards Air Force Base in California, to simulate the KLOTZ Tunnel Explosion Test conducted at China Lake in 1988. These tests were conducted at 20:1 prototype-to-model scale by reducing both the geometric and strength related material properties of the full scale structure. The mass density scale factor was kept at unity. Two of the scaled model tests were conducted at the exact loading densities as that of the prototype. One test was conducted at the same loading density as the prototype but changing the dip angle of major joints in the geologic system. Two tests were conducted at lower loading densities compared to that of the prototype. Fragment recovery was made in one 20° radial extending from the axis of the structure in each case.

2.3 AIR DRAG

Observations made from the recent US Air Force tests on munitions magazines were used to demonstrate a systematic approach for analysis of the blast-induced fragments. Because the analyses become more involved in the scaled model investigations, the emphasis is placed on those tests. Attempts are made to elaborate on the influence of air drag on fragment size and provide a rationale for accounting and/or eliminating the influence of such factors on the analysis of hazardous effects of ejecta.

It is widely recognized that air drag exerts a considerable influence on dimensionally small and linear objects moving in air at high speeds. Furthermore, the influence of air drag on the path of the small objects, such as blast-induced fragments, is inversely proportional to the size of the flying material. As evidenced from the recent tunnel explosion and munitions storage module (MSM) tests, the blast-induced fragments with mean size of even less than 5-cm (2-in) may be hazardous based on the DOD Explosive Safety Standards for hazard classification. Therefore, for accurate prediction of the quantity-distance and probabilistic estimation of post-blast fragment distribution, it is important to investigate the effects of air drag on movement of broken debris originating from detonations within structures.

The extent of the retarding effects of air on a fragment in motion depends on the relation between its linear dimension, density, and speed of movement. Resistive forces experienced by all moving objects in gaseous or fluid space can be attributed to the medium's viscosity and flow retardation, referred to as the "friction drag" or **drag coefficient** and **pressure drag**, respectively.

The Reynolds number (R_e), is the ratio of the inertia forces to the viscous forces. It is a convenient parameter that relates the effects of the resistive forces due to viscosity in the air to the fragment size, density, and velocity.

Technically speaking, the term "viscosity" (also called "absolute" or "dynamic viscosity") of the medium should be differentiated from its "kinematic viscosity" which is of interest in our analysis. The **viscosity** of a fluid is that property which determines the magnitude of its resistance to a shear force and is directly proportional to the resulting rate of deformation of a Newtonian fluid. These relationships are shown below:

Newton's Law of friction:

$$\tau = \mu(du/dy) \quad \ldots\ldots \quad (1)$$

where:

τ = shear stress

(du/dy) = velocity gradient normal to boundary

μ = dynamic (absolute) viscosity - measure of fluid viscosity.

The **kinematic viscosity (υ)**, however, is the ratio of dynamic viscosity to fluid mass density (ρ) given by:

$$\upsilon = \mu/\rho \quad \ldots\ldots \quad (2)$$

The units of the dynamic (absolute) viscosity, μ, and kinematic viscosity, υ, are given in the following table.

TABLE 1. UNITS OF DYNAMIC (ABSOLUTE) AND KINEMATIC VISCOSITY

VISCOCITY	ABSOLUTE (μ)	KINEMATIC (υ)
ENGLISH	lb-sec./ft^2 (slug/ft-sec.)	ft^2/sec.
METRIC	dyne-sec./cm^2 (poise)	cm^2/sec. (stoke)
Kinematic Viscosity of Air, υ_{air} = 0.14 cm^2/sec. (0.02-in^2/sec.)		
Density of Air, p_{air} = 1.29 kg/m^3 (0.0805 lb/ft^3)		

For a case when a fragment with a mean dimension, d_f, traveling at a velocity, v, the dimensionless Reynolds Number, R_e, can be used to establish a correlation between the characteristics of the flying object and the medium as shown in Equation (3).

$$R_e = vd_f/\upsilon \quad (3)$$

Results of numerous experiments conducted in a vacuum and other media show that the viscosity of the medium plays a dominant role for Reynolds Number less than 1000 ($R_e < 1000$). As shown in Table 1, the kinematic viscosity of the air is about 0.14 cm^2/sec. Substituting these values of R_e and υ into Equation (3), the critical values for the products of fragment mean dimension and velocity, i.e., $d_f v$, can be determined as follows:

$$d_f v = 140 \text{ cm}^2/\text{sec.} \quad (4)$$

and

$$d_f v < 140 \text{ cm}^2/\text{sec} \quad (5)$$

or

$$d_f v > 140 \text{ cm}^2/\text{sec.} \quad (6)$$

For the cases represented by Equation (5), it can be deduced that the viscosity of the medium is the dominant factor and the drag is then directly proportional to the fragment velocity. For cases represented by the Equation (6), the effect of viscosity in comparison with the dynamic head is insignificant and therefore, the air drag force is proportional to the square of the fragment velocity.

Attempts have been made to calculate expressions for air drag on prototype rock fragments with average sizes exceeding 1-cm (0.38-in). The word "prototype" is mentioned herein to highlight the importance of changing the scale in experiments where results of scale-model tests are to be analyzed. In such cases, appropriate scale factors should be used to convert the size of the fragments in the model test to its respective prototype size before accounting for the effects of air drag. The blast-induced fragment with mean linear size less than 1-cm (0.38-in) may be considered in physical modeling experiments and have to be scaled up accordingly for hazardous effects analyses.

For prototype fragments measuring d_f = 1-cm (0.38-in), the maximum velocity (v_{max}) at which air drag will vary according to the quadratic law, can be found by substituting d_f = 1-cm (0.38-in) in the Equation (4). Therefore,

$$v_{max} = \{140 \text{ cm}^2/\text{sec.}\}/\{1\text{cm}\} = 140 \text{ cm/sec.} = 1.4 \text{ m/sec.} \quad (7)$$

It should be noted that for fragments with mean size greater than 1-cm (0.38-in) the velocity will be still lower.

By considering the quadratic law of resistance for actual conditions of explosions, Chernigovskii (1970) expressed the air drag in quadratic form by the following expression:

$$F_{air} = c_x S_f \ (p_{air} v^2)/2 \quad \text{. . . . .} \quad (8)$$

where:

c_x = Drag Coefficient (dimensionless)

S_f = Mid-Section Area of Fragment Perpendicular to the Velocity Vector

F_{air} = Air Drag Force

p_{air} = Mass Density of Air

The deceleration due to air drag , J_{air}, can be obtained by dividing each side of the Equation (8) by the fragment mass, M. Therefore,

$$F_{air}/M = (c_x S_f \ p_{air} \ v^2)/2M \quad \text{. . . . .} \quad (9)$$

or

$$J_{air} = b_d \ v^2 = c_x \ (p_{air} v^2/2)(S_f/M) \quad \text{. . . . .} \quad (10)$$

where:

$$b_d = (c_x \ p_{air/}/2)(S_f/M) \quad \text{. . . . .} \quad (11)$$

The term b_d is called the "drag factor" and depends on the shape and mass of the fragment. The quantity (M/S) is referred to by Chernigovskii (1970) as **"specific load**" and is calculated by the quantity of rock mass per square meter of the middle cross-section.

From Equations (10) and (11), it is obvious that the magnitude of the deceleration quantity, J_{air}, diminishes as the mass of the fragment becomes larger or density increases for the same S_f value. Also, the specific load is inversely proportional to the air drag. The mean value of specific load at a given point of the trajectory (refer to Figure 1) can be calculated by the following relationship:

$$M/S_f = ph \quad \text{. . . . .} \quad (12)$$

where h is the thickness of the moving volume of rock fragment in the direction of the fragment velocity.

Internal detonation within a "responding" shallow underground chamber with a high loading density may result in initial disintegration of the cover rock. However, during the post blast phase, the fragmented rock mass moving in air is compacted, resulting in the specific load increasing and a consequent decrease in the effects of air drag. Several other factors also enter the equation of airborne blast-induced fragments which make the incorporation of the opposing force and air drag difficult for both model and prototype cases. These factors include:

- The soil, rock, and concrete materials are crushed into fragments of different sizes, ranging from specks of dust to ejecta several meters in length. In addition, the shape of the fragments generated differ greatly (Baron, 1960). Because the extent of the retarding force depends on the shape and mass of the fragments (primary and secondary), it becomes very difficult to calculate the air drag for the entire mass of ejecta originating from the PES. Therefore, other simplifying approaches are needed that are based on the characteristics of the PES, and on the initial conditions. These can be determined and defined prior to the analysis.

- The initial velocities of ejecta cannot be determined with adequate accuracy. Although fast-frame (high speed still and movie) cameras and formula are available for calculating the initial velocity of projection, they only hold for the **throw-front**. Velocities of ejecta behind the throw-front vary considerably. Errors in evaluating the initial velocity leads to wide errors in calculating the quantity-distance. For example, if the initial velocity of projection is known within ±10% accuracy, it leads to an error of ±20% in the estimated value of the range of scatter for the case of very large fragments.

- Ejecta moving in the air collide with one another. As a result, the fragment velocities change drastically in magnitude and direction during their flight. Also, interference is observed when ejecta move in the form of a solid mass. Large perturbations of travel paths are caused by the bursting out of explosion products ejected at a velocity considerably greater than the velocity of the individual ejecta. The explosion products impart a very high velocity to the ejecta traveling with them. As a result, a cloud of fast- flying fragments is formed in the front of the main mass of exploded rock. This phenomenon was clearly observed during the KLOTZ Tunnel explosion test in China Lake, California.

- The air between fragments moving at short distances from each other is also set in motion, which considerably changes the initial flying conditions and interaction with the medium and other fragments. In particular, as observed from high speed photography, a continuous stream of soil/rock is usually divided into a number of cone-shaped jets, some of which move ahead of the main body of ejecta. A theoretical investigation of this process was first reported by Pokrovskii (1959).

The main problem in determining the constitutive laws of movement of ejecta or debris originating from the ground surface or subsurface and projected in the air (ballistics) cannot be formulated without a stagewise division of the problem. This simplifies the process of detonation by reducing the yield or net weight of explosives. Clearly, the scale model testing based on physical modeling under 1-g provides an attractive alternative to support such studies.

Furthermore, for detonation within responding underground facilities that have high explosive loading densities, an extremely complex interaction between the fragmented mass, products of the explosion, changes in air drag forces and induced air turbulence, is created. This makes it practically impossible to define a single-valued function describing the air drag forces or coefficients. In addition, applications of ballistics or projectile theories for the analysis of blast-induced fragments may not be appropriate for the reasons discussed above. For scale model testing, the impact of air drag on the airborne fragment is very small and can be neglected in calculations related to prediction of the prototype impact energy. This is mainly attributed to the size effects and initial velocities of the induced ejecta which are at the order of hundreds of feet per second--similar to any other secondary fragments.

Because of the irregular shape of the blast-induced fragments, shape factors are used to establish a correlation between the fragment mass and its length dimensions. Swisdak (1991) proposed a shape factor function relating the debris weight with length dimensions. This function has a general form given by the Equation (13).

$$M = B\, p_c\, L^3 \quad \ldots\ldots\ldots \quad (13)$$

where:

M	=	Debris Mass or Weight
B	=	Shape Factor
p_c	=	Debris Mass or Weight Density
L	=	(Debris Length * Debris Width * Debris Thickness)$^{1/3}$

In Equation (13) Swisdak (1991) represented the shape factor as a fraction of the volume of the box determined by the debris when the box is filled by the debris of mass M and density p_c. The debris dimensions (length, width, and thickness) specify a box size just large enough to contain the debris as shown in Figure 2.

The average size of the fragment, d_f, is the size of a cube having a volume equal to the volume of a parallelepiped circumscribing the given fragment.

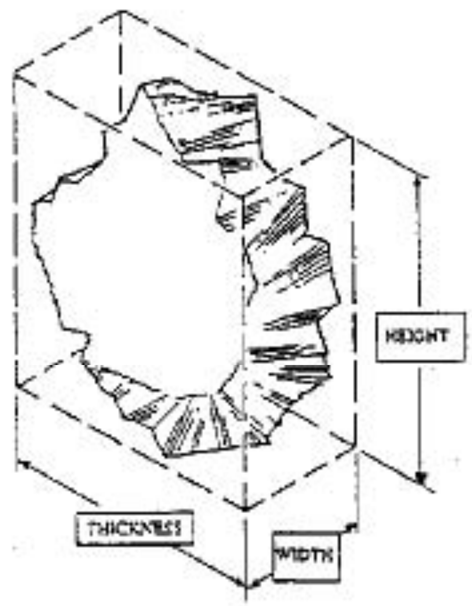

FIGURE 2. SHAPE FACTOR MEASUREMENTS (SWISDAK, 1991).

Studies conducted by Baron (1960) on fragment "lumpiness" and methods of its measurement revealed that the most probable shape for the ratio between its three dimensions a, b, and c, is expressed by the proportion a:b:c = 1.6:1:0.6. As the true volume of the fragment is approximately 2.2 times less than the volume of the circumscribed parallelepiped, then

$$d_f = (2.2\, U_f)^{1/3} = 1.3(U_f)^{1/3} \quad (14)$$

where U_f is the true volume of the fragment.

The moving fragment rotates in an irregular fashion. Therefore, the area in the middle section, S_f, perpendicular to the velocity vector will vary in time and space, from a maximum value $S_{f(maximum)}$ to a minimum value $S_{f(minimum)}$, during the fragment flight . The quantity

$$S_f = 0.6\, d_f^2 \quad (15)$$

can be taken as the mean value of S_f based on the proof provided by Baron (1960).

On the basis of the "Law of Fragmentation," (Khanukaev, 1962) the mass of a fragment can be expressed by the following equation:

$$M = p d_f^3/2.2 \quad (16)$$

Therefore,

$$M/S_f = (d_f\, p)/1.3 \quad (17)$$

Substituting into Equation (11)

$$b_d = 0.66\, (c_x/d_f)(p_{air}/p) \quad (18)$$

According to the fundamental law of ballistics (Okunev, 1940), the drag coefficient for fragments of different shapes varies from 1.2 to 1.8. The mean value can be taken as $c_x = 1.5$ and $p_{air} = 1.29$ kg/m^3. Substituting into Equation (18)

$$b_d = 1.3/(d_f\, p) \quad (19)$$

where d_f is measured in meters and p in kg/m^3. A similar formula can be derived in the English system of units. The quantity b_d has units of (length)$^{-1}$.

3. FRAGMENT ANALYSIS FROM SCALED MODEL TESTS

Assuming constant gravitational acceleration and no drag forces, the simple equations governing the final (terminal) velocity (V) of a moving object and its vertical distance travelled (s) are given by:

$$V = V_0 + (\text{Acceleration}) \times (\text{Time}) \quad \ldots\ldots (20)$$

and

$$s = V_0 \times (\text{Time}) + 1/2\,[(\text{Acceleration}) \times (\text{Time})^2] \quad \ldots\ldots (21)$$

Figure 1, shown earlier, is a simplified representation of a discrete fragment moving in air with an initial velocity of V_0 in a direction making an angle θ with the horizontal. The component of the velocity in the horizontal direction is $\mathbf{V_0 \cos\theta}$. The component in a vertical direction is $\mathbf{V_0 \cos (90^\circ - \theta) = V_0 \sin\theta}$. The acceleration in the vertical direction is **-g**. Therefore, the vertical velocity V at the end of time t is given by:

$$V = V_0 \sin\theta - gt \quad \ldots\ldots (22)$$

and the vertical distance (s) at the end of the time is given by:

$$s = tV_0 \sin\theta - 1/2gt^2 \quad \ldots\ldots (23)$$

The horizontal component of velocity, $V_0\cos\theta$, remains constant in magnitude since there is no component of gravity in the horizontal direction.

The vertical velocity at the maximum height A, Figure 1, is zero. Therefore,

$$V = V_0 + (\text{Acceleration}) \times \text{Time} \quad \ldots\ldots (24)$$

or

$$0 = V_0 \sin\theta - gt \quad \ldots\ldots (25)$$

which results in time to reach the maximum height of:

$$t = V_0 \sin\theta / g \quad \ldots\ldots (26)$$

When a fragment reaches the ground at a time corresponding to $D_{horizontal}$ (considering Figure 1 with $\phi = 0$), the vertical distance (s) travelled is zero, thus, from Equation (23)

$$0 = tV_0\sin\theta - 1/2gt^2 \quad (27)$$

and

$$t = (2V_0\sin\theta)/g \quad (28)$$

Therefore,

$$\textbf{Horizontal Distance Travelled} = \text{range of fragment displacement} \quad (29)$$
$$= \text{Horizontal Velocity x Time}$$
$$= V_0\cos\theta \times (2V_0\sin\theta)/g$$

$$D_{horizontal} = (V_0^2/g)\sin 2\theta \quad (30)$$

Since the maximum magnitude of $\sin 2\theta$ is 1, the angle $2\theta = 90$ degrees for this case. Thus, for a given velocity of throw, the maximum range of fragment displacement is at a 45 degree angle to the horizontal.

For scaled model tests ejecta greater than 2.5 gm (0.1 ounce) were collected and used for subsequent analysis. The material density and mechanical properties of the ejecta are based on index testing or laboratory characterization.

For the irregular size fragments, the average size (d_f) is used in Equation (14) to determine the average volume (U_f). Knowing the density, the mass M for the model at a given location is calculated. Alternatively, Equation (16) can then be used to determine the average mass for the model test fragments directly.

The values obtained for the M_{model} are multiplied by the mass scale factor to determine the prototype mass. The mass scale factor is the product of density and length-cubed scale factors ($p^* l^{*3}$). The horizontal distance travelled is the sloped distance multiplied by the cosine of the vertical angle. The uncertainties associated with the size effects, air drag coefficients and pressure exerted by the explosion products are not taken into account in these analyses. This is because the ejecta have lower initial speed and less explosives (by weight) were used for events simulation.

The most severe conditions of throw, i.e. conservative values for the range of ejecta on a horizontally flat ground surface (ϕ = 0 in Figure 1), θ = 45 degrees were assumed. Therefore, Equation (30) reduces to

$$D(\text{Maximum})_{\text{horizontal}} = 1.1\ V_0^2/g \quad \dots\dots \quad (31)$$

From Equation (31), the initial velocity V_0 for a maximum ejecta range and throw angle can be calculated and substituted in Equation (22) to determine the terminal velocity at impact for each fragment. The terminal velocity is scaled up by the square-root of geometric scale factor $(\ell^*)^{1/2}$ (where velocity scale factor is equal to squared root of linear dimension scale factor or $v^*=(\ell^*)^{1/2}$) to determine the terminal velocity of the prototype. Knowing the prototype mass and terminal velocity, the resulting impact energy (1/2 mv^2) can be calculated. The optimum range is determined for the Q-D based on the limit of 79 joules (57 lb-ft).

The derivations for the general cases where the ground slope is not zero is shown in Figure 1 and Figure 3. As shown in Figure 3, if the ground surface slopes at an angle ϕ, D is the main distance to be measured. This distance can be computed by transforming

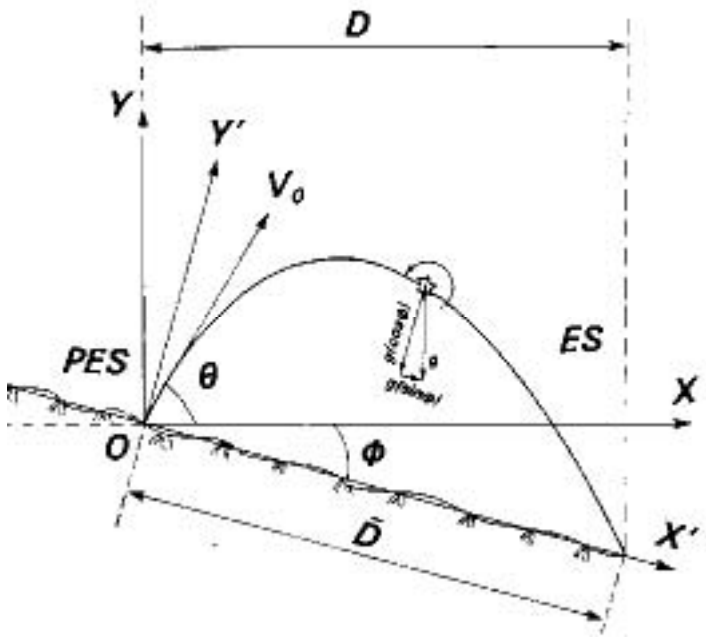

FIGURE 3. SIMPLIFIED REPRESENTATION OF FRAGMENT TRAJECTORIES ON AN INCLINED SURFACE.

the parameters into the X'-Y' coordinate system. The equation analogous to Equation (28) is

$$t = 2V_0\sin(\phi + \theta)/(g\cos\phi) \quad (32)$$

The distance, D, is

$$D = [V_0\cos(\theta + \phi)]t + 1/2[(g\sin\phi)t^2]$$
$$= \{[2V_0^2\cos(\theta + \phi)\sin(\theta + \phi)]/[g(\cos\phi)]\} + \{[2g\sin(\phi)V_0^2\sin^2(\phi + \theta)]/[g^2\cos^2(\phi)]$$
$$= [V_0^2\sin2(\theta + \phi) + 2V_0^2\tan\phi\sin^2(\theta + \phi)]/[g(\cos\phi)] \quad (33)$$

For a given slope angle, ϕ, the value of θ that maximizes D can be found from

$$dD/d\theta = 0 \quad (34)$$

$$= V_0^2/g\cos\phi)[2\cos2(\theta + \phi) + 4\tan\phi\sin(\theta + \phi)\cos(\theta + \phi)] = 0$$
$$= \cos 2(\theta + \phi) + \tan\phi\sin2(\theta + \phi) = 0$$
$$= 1 + \tan\phi\tan2(\theta + \phi) = 0$$
$$= \tan2(\theta + \phi) = -1/\tan\phi$$

which results in the value of θ of

$$\theta = -\phi + 1/2[\tan^{-1}(-1/\tan\phi) \quad (35)$$

For the case of zero slope, $\phi = 0$, and θ becomes

$$\theta = (1/2)\tan^{-1}(\infty) = (1/2)(\pi/2) = \pi/4 = 45^o \quad (36)$$

For $\phi = 30^o$ for example, the value of θ that maximizes D using Equation (35) is:

$$\theta = -30 + (1/2)\tan^{-1}(-1/\tan30) = 30^o$$

for $\phi = 45^o$,

$$\theta = -45 + (1/2)\tan^{-1}(-1/\tan45) = 22.5^o$$

4. FRAGMENT ANALYSIS

The goals of fragment (debris) analysis described in this section are to determine hazardous fragment distribution (density) and maximum debris thrown range. Following an explosion test (event), debris recovery are made by measuring the bearings and distances of all the "**observed**" fragments within a pre-determined sector. For many of cases mechanical breakages of fragments occur upon impact on the ground resulting in multiplication of the fragment frequency by one or more magnitudes. Such occurrences should be clearly marked in the field book and are to be taken into account for the Q-D analyses.

The maximum range for the prototype fragment recovery is dictated by the minimum debris mass and terminal velocity that induces a kinetic energy of 79 joules (58 foot-pound) upon impact. This requirements will lead to calculation of a fragment average size of 1.3-mm (0.03-in) as the cut-off distance (range) for the model tests debris recovery.
As shown by Bakhtar (1995) the impact energy of a fragment is scaled using the following relationship

$$\frac{(ENERGY)_{PROTOTYPE}}{(ENERGY)_{MODEL}} = m^{*} \iota^{*2} t^{*-2}$$

Using the above equation, the minimum kinetic energy associated with a lethal ejecta missile fragment originating from the model tests can be determined as follows:

$$(\text{KINETIC ENERGY})_{\text{MODEL}} = (\text{KINETIC ENERGY})_{\text{PROTOTYPE}} (m^{*}\iota^{*2}t^{*-2})^{-1}$$

or

$$(\text{KINETIC ENERGY})_{\text{MODEL}} = 79 \{(p^{*}\iota^{*3})\, \iota^{*2}(\iota^{*1/2})^{-2}\}^{-1} \tag{38}$$

where, p^{*} and ι^{*} are density scale factor and geometric scale factor, respectively. In practice, the density scale factor is very close to unity for cementiteous based material models and can be considered to be one.

From Equation (14), volumes and weights of fragments at cut-off ranges (maximum distance from respective portal) can be calculated and scaled up using appropriate scale factors to arrive at corresponding prototype values.

The DOD Ammunition and Explosives Safety Standards defines a hazardous fragment as one having a kinetic energy upon impact greater than 79 joules (58 ft-lb). The kinetic energies of impacting materials is given by the Equation (39)

$$\text{Kinetic Energy} = \tfrac{1}{2}\{(m)\,(v^2)\} \tag{39}$$

With a fragment mass of 27.28 g (0.06 lb, 0.02728 kg) the impact velocity at the maximum fragment range is 76 m/sec (249 ft/sec).

5. FRAGMENT LAUNCH ANGLE AND INITIAL VELOCITY

Estimates of blast-induced fragment launch angles and initial velocities have traditionally been made using the theoretical travel distance and where possible the terminal velocity and associated impact energy. However, as indicated in Section 2.3, ejecta moving in air collide with one another, resulting in drastic changes in magnitude and direction of fragment velocity. Furthermore, from the high speed films made during the scaled model explosion tests performed for the US Air Force, interference with the nature of movement and large perturbation of travel paths caused by bursting out of explosion products are observed. Therefore, it is the authors' opinion that such measurements are not warranted and should be eliminated in the future tests. The high cost of making such measurements and expenses associated with tedious and time consuming subsequent analyses should be eliminated in planning future tests. Instead, more money should be allocated to enhanced the instrumentation scheme and increased use of the active gages around test beds. In this way, more information and field data on the blast environment can be obtained which directly impact our understanding of the safety around the "clear zone".

It should be pointed out that, "traditionally", measurements of launch angle and initial velocities are made using high speed films with a "range-pole" in the picture to be used latter as the scale for the photo analysis. In general, the accuracy by which these measurements are made is very much controlled by the ability to initiate the measurement as close as possible to the test bed floor. In many instances such measurements are impossible to make because of the dust cloud formed on the surface following the detonation. For the five scale model tunnel tests conducted for the US Air Force, a series of fast frame cameras located 30.5-m (100-ft) away perpendicular to the chamber-portal axis were used to capture the events. Two range-poles were installed along the extended axis of tunnel/chamber on each test bed to provide the necessary scale and facilitate the ease of fragment velocity determination. An analytical projector was used for the analysis of the fast frame films.

By tracking a discrete fragment in space-time, one should be able to obtain the best estimate of initial velocity and launch angle. Many hundreds of fragments radiating from the PES can be chosen for such calculations. However, experience and judgment should be used to select a suite of appropriate ejecta for such analyses.

6. REMARKS

Based on the foregoing discussion, it is clear that additional research needs to be performed for better prediction of the hazardous effects of the blast-induced fragments. The next generation engineered systems (above- and underground magazines) will be very complex in terms of construction materials and design. The chemical composition of the stored explosives are also very complex and, as a result, field tests are the only source of reliable data for performance assessment of storage magazines. The cost associated with such field tests can be drastically reduced by conducting tests at reduced scale under normal gravity.

Also, from the discussion presented in the preceding pages on the blast-induced fragments originating from detonation of an aboveground or underground munitions storage magazines, the following conclusions are drawn:

1. It is impossible to define a single-valued function describing air drag forces or coefficients.

2. Application of ballistics or projectile theories for analysis of ejecta may not be appropriate.

3. For physical modeling experiments, the impact of air drag is small and can be neglected for impact energy calculations.

4. Shape factor function proposed by Swisdak (1991) can be used for estimating weight of fragments with minimum linear dimension greater than 1-cm (0.4-in).

5. Volume and weight of debris with maximum linear dimension less than 1-cm (0.4-in) can be estimated using Baron (1960) fragment lumpiness approach discussed by Bakhtar (1993).

6. Physical modeling technique under 1-g (normal gravity) provides a cost-effective approach for studies related to assessment of hazardous effects of blast-induced fragments.

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